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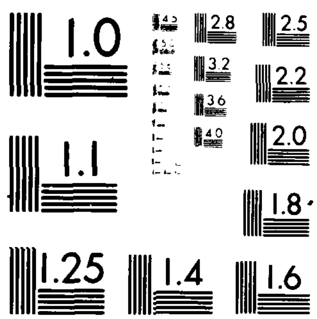

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Lightning flashes have been observed to be induced by large-yield nuclear detonations in the Pacific. Previous researchers have judged a vertical gradient of 100 kV/m to be necessary to induce the strokes, but have predicted EMP-induced fields of only about 30 kV/m. In this report an improved model of the EMP is developed which predicts vertical electric fields up to an order of magnitude higher than previous estimates. The new predictions

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exceed the 100-kV/m threshold for lightning stroke initiation and justify the hypothesis of EMP-induced lightning.

CONTENTS

TABLE

A

1. INTRODUCTION

Lightning flashes have been observed to be induced by large-yield surface nuclear detonations in the Pacific. A paper by Uman et al[1] explored this phenomenon and attempted to explain the flashes as a consequence of the nuclear radiation-induced electromagnetic pulse (EMP) generated by the burst, with the Mike shot of Operation Ivy taken as a specific example for this hypothesis. Uman's results were suggestive, but fell short of the magnitude and duration required to fully justify the hypothesis. Because the observed lightning flashes developed over a period of several milliseconds and endured for about 75 ms, EMP electric fields necessary to induce the lightning must also have a similar duration in order to sustain the current flow of the discharge. Uman judged a vertical gradient of 100 kV/m to be necessary to induce the strokes. The EMP electric fields used by Uman were obtained by Gilinsky[2] for prompt gamma rays, attaining only 30-kV/m levels and lasting only for microseconds because of the short duration of source currents and because the associated air conductivity quickly shorts out the residual fields.

Recent work by Scheibe and Longmire[3] considered secondary gamma rays due to ground capture of thermalized neutrons from the burst as the source of EMP source currents and ionization in the air for several milliseconds after the burst. With Gilinsky,[2] they used the radial Compton electron current J_r divided by the air conductivity σ as an estimate of the electric field strength. They pointed out that the direction of the lightning strokes dictates an unexpected air chemistry concerning the densities of ions and free electrons, possibly due to a buildup of HNO_3 in the air and consequent rapid attachment of free electrons to HNO_3. On this basis, they attempted to determine whether the large electric fields necessary to produce lightning might have been caused by an ion-dominated conductivity much smaller than for previous electric field estimates using electron-dominated conductivity. However, their analysis of the formation of HNO_3 yielded concentrations low enough to support an electron-dominated conductivity, and their predicted field values fell short of those necessary to produce the Mike lightning strokes.

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[1] *M. A. Uman, D. F. Seacord, G. H. Price, and E. T. Pierce, Lightning Induced by Thermonuclear Detonations, J. Geophys. Res., 77 (1972), 1591 to 1596.*

[2] *V. Gilinsky, Kompaneets Model for Radio Emission from a Nuclear Explosion, Phys. Rev., 137A (1965), A50 to A55.*

[3] *M. Sheibe and C. Longmire, The Effect of Ionization-Induced Smog on EMP Environments, Report MRC-N-362, Mission Research Corporation, Santa Barbara, CA (February 1979).*

The purpose of this report is to present a revised model of the EMP which attains the necessary electric field magnitudes and fully justifies the hypothesis that the Mike lightning strokes were induced by EMP. First, a more accurate expression for the electric field strength will be derived. Second, an alternate interpretation of the air chemistry will be presented. Finally, the resultant electric field strengths will be found to be up to an order of magnitude greater than previous results.

2. DEVELOPMENT OF MODEL

2.1 Derivation of Electric Field Strength Equation

Secondary gamma rays due to ground capture of thermalized neutrons have been proposed by Scheibe and Longmire[3] as the source of electric fields strong enough to induce lightning on a time scale of milliseconds. An approximate semistatic solution to Maxwell's equations will now be derived that is valid for this time regime after the nuclear burst. In MKS units, Maxwell's curl equations in air may be written

$$\mu_H \frac{\partial H}{\partial t} = - \nabla \times \vec{E} \tag{1}$$

and

$$\varepsilon_o \frac{\partial E}{\partial t} = \nabla \times \vec{H} - \vec{J}_c - \sigma\vec{E} \ , \tag{2}$$

where $\vec{E}$ and $\vec{H}$ are electric and magnetic intensities, respectively, μ_H and ε_o are permeability and permittivity of free space ($4\pi \times 10^{-7}$ H/m and 8.85×10^{-12} F/m), t is time in seconds, $\vec{J}_c$ is the driving Compton current (A/m^2), and σ is the air conductivity (mho/m).

With assumptions of azimuthal symmetry about the burst, vanishing azimuthal component of the driving current $\vec{J}$, and scalar air conductivity σ, we have in spherical coordinates centered at ground zero the transverse magnetic (TM) or electric multipole equations:

$$\mu_H \frac{\partial H_\phi}{\partial t} = - \frac{1}{r}\frac{\partial}{\partial r}\left(r\ E_\theta\right) + \frac{1}{r}\frac{\partial E_r}{\partial \theta} \ , \tag{3}$$

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[3] *M. Sheibe and C. Longmire, The Effect of Ionization-Induced Smog on EMP Environments, Report MRC-N-362, Mission Research Corporation, Santa Barbara, CA (February 1979).*

$$\varepsilon_o \frac{\partial E_r}{\partial t} = \frac{1}{r \sin\theta} \frac{\partial}{\partial\theta} \left(\sin\theta\ H_\phi\right) - J_r - \sigma E_r \ , \tag{4}$$

$$\varepsilon_o \frac{\partial E_\theta}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} \left(r\ H_\phi\right) - J_\theta - \sigma E_\theta \ . \tag{5}$$

At times greater than about 0.1 ms after the burst, the time derivative terms in equations (3) to (5) become small for fields within several kilometers of the burst (since ct >> r). Rewriting (4) and neglecting the time derivative gives

$$\frac{1}{r \sin\theta} \frac{\partial}{\partial\theta} \left(\sin\theta\ H_\phi\right) \simeq J_r + \sigma E_r \ . \tag{6}$$

To first order, the conduction current term E_r in (6) may be neglected since both σ and E_r become small at late times, so that approximately

$$\frac{1}{r \sin\theta} \frac{\partial}{\partial\theta} \left(\sin\theta\ H_\phi\right) \simeq J_r \ . \tag{7}$$

At a distance from the burst of more than a few gamma mean free paths, the EMP sources are caused predominantly by multiply scattered gammas instead of singly scattered gammas. For this reason, and since the multiply scattered gammas originating from ground capture of neutrons have lost most of their initial upward collimation, the radial Compton current J_r becomes nearly independent of θ. With the approximation that J_r is independent of θ, integration of (7) from the vertical ($\theta = 0$) to the ground surface ($\theta = \pi/2$) gives

$$\int_0^{\pi/2} \partial\left(\sin\theta\ H_\phi\right) \simeq rJ_r \int_0^{\pi/2} \sin\theta\ \partial\theta$$

$$\left[\sin\theta\ H_\phi\right]_0^{\pi/2} \simeq rJ_r \left[-\cos\theta\right]_0^{\pi/2}$$

$$H_\phi\left(\theta = \pi/2\right) \simeq rJ_r \ . \tag{8}$$

Rewriting (5) and neglecting the time derivative gives

$$- \frac{1}{r} \frac{\partial}{\partial r} \left(r \; H_\phi \right) \simeq J_\theta + \sigma E_\theta \; . \tag{9}$$

Using expression (8) for H_ϕ at the ground and assuming a form

$$J_r = J \exp(- r/\lambda)/r^2 \tag{10}$$

for the radial current, where λ is the effective attenuation length for neutron capture gammas, we have

$$\begin{aligned} \frac{\partial}{\partial r} \left(r \; H_\phi \right) &\simeq \frac{\partial}{\partial r} \left[J \exp(-r/\lambda) \right] \\ &\simeq - J \exp(-r/\lambda)/\lambda \end{aligned} \tag{11}$$

or

$$\frac{\partial}{\partial r} \left(r \; H_\phi \right) \simeq - r^2 J_r/\lambda \; . \tag{12}$$

Substitution of result (12) into equation (9) gives

$$\frac{rJ_r}{\lambda} \simeq J_\theta + \sigma E_\theta \; , \tag{13}$$

or

$$E_\theta \simeq \frac{1}{\sigma} \left(\frac{rJ_r}{\lambda} - J_\theta \right) . \tag{14}$$

For currents due to ground capture of thermalized neutrons, J_r is negative and J_θ is positive and of approximately the same magnitude as J_r. For $r >> \lambda$, J_θ may be omitted from (14) with little error, yielding the approximate result for the theta electric field at the surface,

$$E_\theta \simeq \frac{rJ_r}{\lambda \sigma} \; . \tag{15}$$

The result, (15), is different by a factor r/λ from the expression J_r/σ previously used.[2,3] Result (15) also applies to secondary gamma sources due to air capture of thermalized neutrons, extending to hundreds of milliseconds after the burst, as well as for ground capture.

2.2 Discussion of Air Conductivity

Since an evaluation of the air conductivity σ is essential to obtain the electric field component E_θ (vertical at the ground), it is necessary to consider in detail the relative contributions of free electrons and ions. It has been pointed out that the circular shape of the Mike lightning strokes, concentric to the burst point, implies an unusual air chemistry at the stroke ranges. The following is presented in review of previous theory. Since the time derivative in equation (3) is virtually zero, we obtain

$$\frac{\partial}{\partial r}\left(r\ E_\theta\right) = \frac{\partial E_r}{\partial \theta}\ . \tag{16}$$

The circular shape of the strokes requires $E_r \ll E_\theta$, so that

$$\frac{\partial}{\partial r}\left(r\ E_\theta\right) \simeq 0\ , \tag{17}$$

or

$$r\ E_\theta \simeq \text{constant}\ . \tag{18}$$

Combining equations (15) and (18),

$$\frac{r^2 J_r}{\sigma} \simeq \text{constant}\ . \tag{19}$$

For (19) to be true, the logarithmic derivative of $1/r^2$ with respect to range r must (approximately) equal the logarithmic derivative of J_r/σ. The logarithmic derivative of $1/r^2$ is

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[2] *V. Gilinsky, Kompaneets Model for Radio Emission from a Nuclear Explosion, Phys. Rev.,* 137A *(1965), A50 to A55.*

[3] *M. Sheibe and C. Longmire, The Effect of Ionization-Induced Smog on EMP Environments, Report MRC-N-362, Mission Research Corporation, Santa Barbara, CA (February 1979).*

$$r^2 \frac{d}{dr}\left(r^{-2}\right) = - 2/r \ . \tag{20}$$

The range dependence of J_r/σ will now be considered. The late-time electronic conductivity σ_e can be written

$$\sigma_e \simeq e\ S\mu_e/\beta \ , \tag{21}$$

where e is the electron magnitude of the charge, S is the ionization rate in ion pairs/m^3-s, μ_e is the free electron mobility in m^2/V-s, and β is the free electron attachment rate in air (usually taken to be about $10^8 s^{-1}$).

The late-time ionic conductivity σ_i can be written

$$\sigma_i \simeq e\mu_i \ (S/\gamma)^{1/2} \ , \tag{22}$$

where μ_i is the average ionic mobility in m^2/V-s and γ is the average ion-ion recombination rate in m^3/s.

To a good approximation, J_r is proportional to S and may be written

$$J_r = - eRS/\nu \ , \tag{23}$$

where R is the average forward range of the Compton electron in meters and ν is the average number of ion pairs created by the Compton electron. If electronic conductivity dominates,

$$J_r/\sigma_e \simeq - R\beta/\mu_e\nu \ , \tag{24}$$

while if ionic conductivity dominates,

$$J_r/\sigma_i \simeq - RS^{1/2} \ \gamma^{1/2}/\mu_i\nu \ . \tag{25}$$

At first appearance, equation (24) does not appear to have any r-dependence, so its logarithmic derivative would be zero in contradiction of (20). On the other hand, in (25) the ionization rate S has a range dependence of the form of (10) since $S \propto J_r$, or

$$S(r) \propto \exp(-r/\lambda)/r^2 , \tag{26}$$

so that

$$J_r/\sigma_i \propto S^{1/2} \text{ or } \exp(-r/2\lambda)/r . \tag{27}$$

The logarithmic derivative of (27) is

$$r\, e^{r/2\lambda} \frac{d}{dr}\left(\frac{e^{-r/2\lambda}}{r}\right) = -\frac{1}{r}\left(1 + \frac{r}{2\lambda}\right) . \tag{28}$$

The attenuation length λ is about[4] 300 m. Using $r = 900$ m for one of the Mike lightning strokes, the logarithmic derivative of J_r/σ_i becomes $-2.5/r$, which is close to the desired value $-2/r$ (from equation (20)). It would thus appear that the circular path of the Mike lightning strokes demands that the air conductivity be dominated by ions rather than free electrons.

Having reviewed previous arguments, Scheibe and Longmire's conclusion must be noted.[3] They maintain that consideration of attachment of free electrons to both molecular oxygen and the HNO_3 predicted to be formed at the lightning stroke ranges nevertheless indicates that the air conductivity is still dominated by free electrons rather than ions. While other mechanisms have been proposed as potential means of reducing the free electron density to the point where the ionic conductivity dominates (e.g., "hot" electron reactions with certain neutral molecules[3]), an alternate theory successfully based on dominant electron conductivity would have immediate appeal. An attempt at such a theory will now be set forth.

Equation (24) for electron-dominated conductivity contains parameters R and ν, which are weakly dependent upon range from the burst; μ_e, which depends upon the electric field strength; and the attachment rate, β, which is due to attachment to O_2 at all but very high radiation dose levels. According to Scheibe and Longmire,[3] the

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[3] M. Sheibe and C. Longmire, *The Effect of Ionization-Induced Smog on EMP Environments*, Report MRC-N-362, Mission Research Corporation, Santa Barbara, CA (February 1979).

[4] H. S. Schechter and M. O. Cohen, *Energy Deposition Rates and Compton Electron Currents from Low-Altitude Bursts as a Function of Source Energy*, U.S. Army, Harry Diamond Laboratories Report, HDL-CR-77-020-1, Mathematical Applications Group, Inc., Elmsford, NY (November 1977).

total dose is high enough at the lightning stroke ranges to cause formation of HNO_3 in the air in such great numbers as to affect the value for β at those ranges, since electrons attach very readily to HNO_3. They estimate the attachment rate to HNO_3 in units of the attachment rate to O_2 to be 1 at 3.5 million rads (Mrd), 2 at 10 Mrd, and 4 at 35 Mrd. They further estimate a linear dependence upon dose at lower dose levels. This dependence of the total attachment rate $\beta = \beta(HNO_3) + \beta(O_2)$ upon dose can be well approximated over the range 1.0 to 35 Mrd by

$$\beta \approx 2\, \beta\left(O_2\right)\left(D/3.5 \times 10^6\right)^{0.4} , \tag{29}$$

where $\beta(O_2)$ is the attachment rate to O_2 and D is the dose in rads. Since the Compton current $J_r(r)$ is proportional to the dose $D(r)$,

$$\beta \propto J_r^{0.4} , \tag{30}$$

so that from (21)

$$\sigma_e \propto J_r^{0.6} , \tag{31}$$

and from (24)

$$J_r/\sigma_e \propto J_r^{0.4} . \tag{32}$$

Thus, we see that for dose levels of 1.0 to 35 Mrd, the buildup of HNO_3 causes a range dependence of the electron attachment rate and an associated range dependence of J_r/σ_e. The logarithmic derivative of the latter is

$$\begin{aligned} J_r^{-0.4} \frac{d}{dr}\left(J_r^{0.4}\right) &= \frac{0.4}{J_r} \frac{d}{dr}\left(J_r\right) \\ &= -\,0.4\left(\frac{2}{r} + \frac{1}{\lambda}\right) , \end{aligned} \tag{33}$$

which for r = 900 m and λ = 300 m yields a value of $-2.0/r$. This value matches exactly the desired value $-2/r$ from equation (20). It is apparent that circularity of lightning bolts concentric to the burst point can be understood in terms of an electron-dominated air conductivity, at least for dose levels above roughly 1 Mrd.

The electric field dependence of the electron mobility also plays a role in determining the circularity of the lightning bolts. These various effects will be gathered together to predict the peak electric field (sect. 3).

3. PREDICTED ELECTRIC FIELD STRENGTH

In order to predict the maximum vertical electric field strength at the Mike lightning bolt ranges, equation (15) is rewritten as

$$E_{\theta} = \frac{rJ_r}{\lambda\left(\sigma_e + \sigma_i\right)} , \tag{34}$$

and (21), (22), and (23) are used to obtain

$$E_{\theta} \; [illegible] \; \frac{[illegible] \, RF}{[illegible] \left[\mu_e + \mu_i [illegible] \right]^{1/2}} \tag{35}$$

We use the previous values r [illegible] 800 m and λ = 500 m, and use R [illegible] 2.0 [illegible] and [illegible] 2 × 10⁴ as typical of the somewhat poorly collimated Compton electrons resulting from ground (or air) capture of thermalized neutrons. The electron mobility μ_e is reasonably well approximated for the electric field strengths considered here by

$$\mu_e = 50.0 \, E^{[illegible]} \tag{3[illegible]}$$

in MKS units, where E is the magnitude of the field strength. Since E_{θ} is the dominate component of the electric field near the ground at late time, E will [illegible] equal to [illegible]. The [illegible] rate [illegible] is about 2 × [illegible] m³/s for [illegible] ions, and the [illegible] mobility is about [illegible] × 10⁻³ [illegible].

The correct [illegible] for the electron attachment rate depends on several factors, [illegible] the concentration of [illegible], the water vapor content [illegible] and the strength of the electric field. The rate for attachment [illegible] will be estimated [illegible] 1 × 10³ s⁻¹. Based on extrapolation of [illegible]'s estimate of 10-Mrd gamma radiation at a 500-m range [illegible] the Mike burst, the dose at a [illegible]0-m range would be [illegible]. [illegible] additional dose of [illegible] would [illegible] received in the next several hundred milliseconds from secondary gamma rays due to air capture of thermalized neutrons. A dose of 0.85 Mrd leads to an attachment rate of $\beta \simeq 1.2 \times 10^8\ s^{-1}$. The ionization rate S was estimated by Scheibe and Longmire to about 6×10^{23} ion pairs/m^3-s, at a 500-m range and 10 ms after the Mike burst, due to gamma radiation. Extrapolation to 900 m yields $S = 5 \times 10^{22}$ ion pairs/m^3-s.

Predicted electric field strengths and ratios of ionic conductivity to electron conductivity are presented in table 1 for ranges of 500, 900, and 1300 m from the burst. Results are given both for unhydrated ions (such that $\gamma \simeq 2 \times 10^{-12} m^3/s$) and for hydrated ions (such that $\gamma \simeq 8 \times 10^{-12} m^3/s$).[5] Although Scheibe and Longmire used the recombination rate for unhydrated ions, this author prefers the rate for hydrated ions, since extensive hydration can occur within a millisecond of the burst.

TABLE 1. CALCULATED RESULTS AT 10 ms AFTER MIKE BURST FOR UNHYDRATED AND HYDRATED IONS

γ (m^3/s)	Range (m)	Dose (Mrads)	Ionization rate (ion pair/m^3-s)	β (s^{-1})	$-E_0$ (kV/m)	σ_i/σ_e
Unhydrated						
2×10^{-12}	500	10.	6×10^{23}	3×10^8	178	0.58
2×10^{-12}	900	0.85	5×10^{22}	1.2×10^8	93	0.58
2×10^{-12}	1300	0.1	7×10^{21}	1×10^8	73	1.14
Hydrated						
8×10^{-12}	500	10.	6×10^{23}	3×10^8	247	0.34
8×10^{-12}	900	0.85	5×10^{22}	1.2×10^8	128	0.34
8×10^{-12}	1300	0.1	7×10^{21}	1×10^8	114	0.72

[5] *C. A. Blank, T. Baurer, M. H. Bortner, and A. A. Feryok, A Pocket Manual of the Physical and Chemical Characteristics of the Earth's Atmosphere, Defense Nuclear Agency Handbook, DNA 3467H, General Electric Co., Philadelphia, PA (1 July 1974), 155.*

Thus, we see that field strengths of the order of 100 kV/m are predicted for the ranges of the Mike lightning bolts (900 to 1380 m),[1] with somewhat stronger fields at closer ranges. The fields are not strong enough to induce a general breakdown throughout the source region, but, as was observed, are strong enough to trigger bolts from instrumentation shelters made of conducting material. A 1/r range dependence of E_θ is necessary to explain the circular lightning bolts. The values for E_θ have approximately a 1/r range dependence from 500 to 900 m, with a somewhat weaker dependence out to 1300 m. In view of the roughness of the calculation, the results seem in reasonable accord with a 1/r range dependence for the ranges of the Mike lightning bolts. It is possible that a more precise calculation of E_θ using better estimates of μ_e, β, and J_θ would produce better agreement.

The air conductivity is dominated by electrons at ranges less than roughly 1300 m and by ions at greater ranges, so that circular lightning bolts should prevail in both regimes. The field strength at ranges much greater than 1300 m appears to become too small to trigger lightning bolts.

In the Scheibe and Longmire estimates of dose, elastic recoil ionization by neutrons was omitted. If a normal neutron energy spectrum is postulated, the dose increases[6] by about 200 percent at 500 m, about 100 percent at 900 m, and about 50 percent at 1300 m. These increased dose values lead to electric field values of 253, 112, and 73 kV/m at 500, 900, and 1300 m for unhydrated ions, with electron and ion conductivities about equal at all three ranges. For hydrated ions, we obtain 390, 164, and 114 kV/m at these ranges, with electron conductivity slightly greater than ionic conductivity at each range. Inclusion of elastic recoil ionization tends to cause more exact conformance to a 1/r range dependence between 900 and 1300 m. Inclusion may not be justified for the Mike burst, however.

Use of equation (15) leads to predicted fields high enough (over 100 kV/m) to support an average free electron energy of about 1 eV. At energies this high, free electrons may enter into reactions with neutral molecules producing negative ions.[3] This may happen fast enough to

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[1] *M. A. Uman, D. F. Seacord, G. H. Price, and E. T. Pierce, Lightning Induced by Thermonuclear Detonations, J. Geophys. Res., 77 (1972), 1591 to 1596.*

[3] *M. Sheibe and C. Longmire, The Effect of Ionization-Induced Smog on EMP Environments, Report MRC-N-362, Mission Research Corporation, Santa Barbara, CA (February 1979).*

[6] *S. Glasstone, editor, The Effects of Nuclear Weapons, U.S. Atomic Energy Commission, U.S. Government Printing Office, Washington, DC (April 1962), 583.*

substantially reduce the free electron density. Evaluation of this effect would require the use of equation (15) or its equivalent and the appropriate reaction rates folded with a Druyvesteyn (not Maxwellian) energy distribution of the "hot" electrons.

4. CONCLUSIONS

An EMP model has been proposed for the Mike shot which predicts vertical electric field strengths of about 100 kV/m, satisfying Uman's criterion[1] for triggering observed lightning flashes, on a time scale of milliseconds in conformance with the duration of the observed flashes. Uman noted that the lightning flashes endured for about 75 ms. This can be understood as an initial breakdown due to ground capture EMP sources on a scale of a few milliseconds, sustained for about 0.05 to 0.1 s by air capture EMP sources which, although somewhat weaker in intensity, are longer lasting.

The model substantially accounts for the observed circularity of the Mike lightning bolts in terms of an electron-dominated air conductivity in the presence of HNO_3. The model does not rule out the possibility, however, of free electron removal through "hot" electron reactions with neutral air molecules, as suggested by Scheibe and Longmire.[3]

These results demonstrate that lightning flashes induced by large-yield surface nuclear detonations can be understood as consequences of sustained radiation-induced EMP fields of about 100 kV/m.

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[1] *M. A. Uman, D. F. Seacord, G. H. Price, and E. T. Pierce, Lightning Induced by Thermonuclear Detonations, J. Geophys. Res., 77 (1972), 1591 to 1596.*

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